TML REPORT No.39
March 30, 1956

SURVEY OF PHYSICAL-PROPERTY DATA FOR TITANIUM AND TITANIUM ALLOYS

TITANIUM METALLURGICAL LABORATORY
Battelle Memorial Institute
Columbus 1, Ohio

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1. Under the general direction of the Steering Group on Titanium Research and Development, of the Office of Assistant Secretary of Defense (R & D), to conduct laboratory investigations directed toward solution of current metallurgical problems involved in the use of titanium.

2. As directed by OAS/D, to assist the Government agencies and their contractors in developing data required for preparation of specifications for titanium metal and titanium mill products.

3. To provide assistance and advice to OAS/D in its appraisal of the Department of Defense research and development program on titanium and make recommendations with respect to the program.

4. To collect and, as directed by OAS/D, disseminate to Government contractors or subcontractors having related Government contracts or subcontracts, available information on the current status of titanium research and development.

5. When directed by OAS/D, to provide technical consulting services to producers, melters and fabricators of titanium metal and designers and fabricators of military equipment containing titanium, on titanium utilization problems, including appropriate consideration of alternate materials.

6. To provide such other research and related services in connection with the titanium program as may be mutually agreed upon between Battelle and the Assistant Secretary of Defense (R & D) or his designee.

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Report on

SURVEY OF PHYSICAL-PROPERTY DATA FOR TITANIUM AND TITANIUM ALLOYS

by

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to

OFFICE OF ASSISTANT SECRETARY OF DEFENSE
FOR RESEARCH AND DEVELOPMENT

Titanium Metallurgical Laboratory
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TABLE OF CONTENTS

LIST OF TABLES

ABSTRACT

A literature survey was made in the TML and other Battelle libraries on physical-property data for titanium and titanium alloys. Data were found and are reported for eighteen properties.

Report on

SURVEY OF PHYSICAL-PROPERTY DATA FOR TITANIUM AND TITANIUM ALLOYS

INTRODUCTION

On September 22, 1955, TML Report No. 15 on "The Engineering Properties of Commercial Titanium Alloys" by M. W. Mote and P. D. Frost was issued by the Titanium Metallurgical Laboratory, Battelle Memorial Institute, Columbus, Ohio. The report presented the mechanical and physical properties of fifteen alloys made by four manufacturers. The data presented were made available by the four manufacturing companies and consisted chiefly of mechanical properties.

This report presents physical properties of titanium and its alloys, obtained by a literature survey in the TML and other Battelle libraries. Physical-property data previously included in the TML Report No. 15 are included in this report.

The data are presented under headings of the respective physical properties. For some properties much data were found while little or no data were found for other properties. In general, few data were found for high-temperature properties.

The data presented in the tables are in similar units and are usually presented at common temperatures for easy comparison. It frequently was necessary to change temperature scales and units. Often original data were replotted in the desired units to permit interpolations at the desired temperatures. In some instances random tabular data were plotted and an arbitrary best curve drawn from which interpolated data were taken.

In many instances differing data were found for the same material and measurements. In most instances these data are shown for purposes of comparison as it was beyond the scope of the present survey to investigate experimental techniques and evaluate the results. Also, some references given are not for the original work, but are quotes or evaluations of the work. Wherever feasible, however, the original reference is given.

Comments on Available Data

The preponderance of available data for titanium and its alloys are for mechanical properties. This is to be expected because in ordinary

engineering problems, mechanical properties are those first sought and used. There is a growing need, however, for physical-property data. This need grows out of design problems where thermal expansion, thermal conductivity, and other physical properties are important, especially at elevated temperatures. Such information should be available if titanium and its alloys are to take their rightful places as materials of construction.

It is probable that physical properties other than those included in this report are available in certain quarters. Inquiries of manufacturers, fabricators, and users are needed to establish the existence of such data and their availability for general publication. A program of physical measurements over an extended temperature range could then be planned to fill the needed gaps.

Composition of Commercial Alloys

Commercial titanium alloys available from the four major producers are given in Table 1. The alloys are identified in each subsequent table of the report under the column headed "Alloy Designation".

GENERAL PHYSICAL PROPERTIES

Boiling Temperature

The boiling temperature of titanium, as reported by Ogden and Gonser[1], ranges from 5900 to 6395 F. No values were found for the boiling temperatures of titanium alloys.

Crystal Structure

Titanium in the alpha phase is close-packed-hexagonal and stable to about 1620 F. The beta phase is body-centered-cubic and stable from about 1620 F to the melting temperature. The lattice parameters of pure titanium are given by Merriman[2], as:

	Alpha	Beta
Lattice constant (c)	4.6833 A	3.3065 A
Atomic diameter (a)	2.9504 A	2.860 A
c/a	1.587	1.156

TABLE 1. COMPOSITION OF COMMERCIAL ALLOYS

Producer and Alloy Designation	Composition (Balance Titanium), weight per cent						
	Al	Cr	Fe	Mn	Mo	Sn	V
Mallory-Sharon Titanium Corporation							
MST-Grade III	--	--	--	--	--	--	--
MST-2Fe	--	--	2	--	--	--	--
MST-2Al-2Fe	2	--	2	--	--	--	--
MST-2.5Fe-2.5V	--	--	2.5	--	--	--	2.5
MST-3Al-5Cr	3	5	--	--	--	--	--
MST-4Mn-4Al	4	--	--	4	--	--	--
MST-6Al-4V	6	--	--	--	--	--	4
3Mn complex	--	1	1	3	1	--	1
Rem-Cru Titanium, Inc.							
RC-55	--	--	--	--	--	--	--
A-70 (was RC-70)	--	--	--	--	--	--	--
A-110AT	5	--	--	--	--	2.5	--
C-110M (was RC-130A)	--	--	--	8	--	--	--
C-110M modified	--	--	--	5	--	5	2
C-130AM (was RC-130B)	4	--	--	4	--	--	--
Republic Steel Corporation							
RS-55	--	--	--	--	--	--	--
RS-70 (A)	--	--	--	--	--	--	--
RS-110	--	3	1.5	--	--	--	--
RS-110A	--	--	--	8	--	--	--
RS-110BX	1	--	--	3	--	--	--
RS-120	--	--	--	7	--	--	--
RS-130	4	--	--	4	--	--	--
RS-140X	5	2	2	--	--	--	--
Titanium Metals Corporation of America							
Ti-75A	--	--	--	--	--	--	--
Ti-100A	--	--	--	--	--	--	--
Ti-125A	--	--	--	--	--	--	--
Ti-130A	--	--	--	--	--	--	--
Ti-140A	--	2.1	2.2	--	2.0	--	--
Ti-150A	--	2.8	1.5	--	--	--	--
Ti-150B	--	3	1.5	--	--	--	--
Ti-155A	5	2	2	--	2	--	--
Ti-155AX	5	1.4	1.3	--	1.4	--	--
Ti-175A	--	--	--	--	--	--	--
Ti-4Al-3Mo-1V	4	--	--	--	3	--	1
Ti-6Al-4V	6	--	--	--	--	--	4

Density

Perhaps the most direct and accurate density measurement of iodide titanium was by Fast[3] who found a value of 0.1628 ± 0.0002 lb/in.^{3}. Cullen[4] states that titanium powder compacted at from 30 to 50 tons/in.^{2} has a density from 0.112 to 0.126 lb/in.^{3}. After sintering for 1 hour or longer at 1650 to 2100 F, the density may increase to 0.161 lb/in.^{3}.

Williams and Jaffee[5] express the change in density of titanium with hydrogen content as:

Density (g/cc) = 4.5549 - 0.0071 x hydrogen content in atomic per cent.

Table 2 gives other data on the density of titanium and titanium alloys.

Isotopic Constitution of Titanium

Skinner, et al.,[6] give the isotopic constitution of titanium as follows:

Mass Number	Mass (Physical Scale)	Per Cent Abundance
46	45.9661 ± 0.00095	7.95
47	46.9647 ± 0.00095	7.75
48	47.9633 ± 0.00048	73.45
49	48.9648 ± 0.00053	5.51
50	49.9623 ± 0.00038	5.34

From these values the chemical atomic weight of titanium is 47.876 compared to the International value of 47.90.

Melting Temperature

Melting temperatures found in the literature for titanium differ widely. It often is difficult to determine if a published melting temperature is for pure (iodide) titanium or commercially pure titanium. Of 17 values given for the melting temperature of pure titanium (assumed pure in some cases), and some values not from original work (quoted from other works not referenced), the average melting temperature is 3165 F. The range was from 3020 F to 3317 F. Averaging five values for commercially pure titanium, with the same uncertainties, gave an average value of 3097 F. The range was from 3040 F to 3135 F.

TABLE 2. DENSITY OF TITANIUM AND TITANIUM ALLOYS

Composition (Balance Ti), weight per cent	Alloy Designation	Density, lb/in.^{3}	Remarks	Reference
Iodide Ti	--	0.1628 ± 0.0002	--	6
Iodide Ti	--	0.163	--	7
99.2Ti	--	0.164	--	7
Commercially pure Ti	Ti-100A	0.164	--	8
Commercially pure Ti	Ti-175A	0.168	--	9
Powder compact, Ti	--	0.112 to 0.126	Compacted at 30 to 50 tons/in.^{2}	4
Sintered powder compact, Ti	--	0.161	Sintered 1 hr at 1650 to 2100 F	4
1.9Al	--	0.167	--	10
2Al	--	0.162	--	11
2Al-2Fe	MST-2Al-2Fe	0.165	--	8,9,12
3Al-5Cr	MST-3Al-5Cr	0.166	--	8,9,12,13,14
4Al	--	0.160	--	11
4Al-4Mn	C-130AM (RC-130B)	0.1633	--	13,14
4.1Al	--	0.162	--	10
5Al-2Cr-2Fe	RS-140X	0.163	--	13,14
5Al-2.5Sn	A-110AT	0.161	--	13,14
5.9Al	--	0.161	--	10
6Al	--	0.159	--	11
6Al-1Si	--	0.158	--	11
6Al-4V	MST-6Al-4V	0.160	--	13,14
7.5Al	--	0.157	--	15
7.9Al	--	0.158	--	10
8Al	--	0.157	--	11
8Al-4Mo	--	0.163	--	11
8Al-1Si	--	0.157	--	11
36Al	--	0.130	--	16
37Al	--	0.137	γ phase	17
0.40C	--	0.166	--	10
0.66C	--	0.164	--	10
0.85C	--	0.164	--	10
3.02Cu	--	0.167	--	10
6.36Cu	--	0.170	--	10

TABLE 2. (Continued)

Composition (Balance Ti), weight per cent	Alloy Designation	Density, lb/in.^{3}	Remarks	Reference
11.5Cu	--	0.173	--	10
38Co	--	0.206	$CoTi_2$	18
38Co	--	0.210	$CoTi_2$, sintered, hot pressed	18
38Co	--	0.202	$CoTi_2$, heat treated	18
2.1Cr-2.2Fe-2.0Mo	Ti-140A	0.1688	--	13,14
2.8Cr-1.5Fe	Ti-150A	0.1668	Other values: 0.166, 0.17, 0.168	13
3Cr-1.5Fe	Ti-150B	0.168	--	9
3Cr-1.5Fe	RS-110	0.168	--	13
4.5Cr-4.5Fe-4.5Mo	--	0.175	--	15
2.5Fe-2.5V	MST-2.5Fe-2.5V	0.167	--	8,9,12
37Fe	--	0.201	$FeTi_2$	18
37Fe	--	0.210	$FeTi_2$, sintered, hot pressed	18
0.002H_2	--	0.164	--	19
0.004H_2	--	0.165	--	19
0.50H_2	--	0.162	--	19
1.11H_2	--	0.160	--	19
1.94H_2	--	0.157	--	19
2.73H_2	--	0.154	--	19
5Mn-5Sn-2V	C-110M, modified	0.171	--	20
7Mn	RS-120	0.170	--	13
8Mn	C-110M (RC-130A)	0.172	--	15,21
30Mo	--	0.199	--	15
30Mo	--	0.195	--	11
38Ni	--	0.203	$NiTi_2$	18
38Ni	--	0.206	$NiTi_2$, sintered, hot pressed	18
38Ni	--	0.208	$NiTi_2$, heat treated	18
1.20V	--	0.1636	Du Pont, arc melted	22
1.20V	--	0.1635	Du Pont, hot rolled	22
2.475V	--	0.1646	Du Pont, arc melted	22
2.475V	--	0.1647	Du Pont, hot rolled	22
3.14V	--	0.1645	Du Pont, arc melted	22
3.14V	--	0.1645	Du Pont, hot rolled	22
4.22V	--	0.1652	Du Pont, arc melted	22

TABLE 2. (Continued)

Composition (Balance Ti), weight per cent	Alloy Designation	Density, $lb/in.^3$	Remarks	Reference
4.22V	--	0.1650	Du Pont, hot rolled	22
5.31V	--	0.1656	Du Pont, arc melted	22
5.31V	--	0.1655	Du Pont, hot rolled	22
5.96V	--	0.166	National Lead material	23
7.55V	--	0.1665	Du Pont, arc melted	23
7.55V	--	0.1666	Du Pont, hot rolled	23
10.6V	--	0.170	--	10
10.9V	--	0.1683	Du Pont, arc melted	23
14.1V	--	0.170	National Lead material	23
14.73V	--	0.1709	Du Pont, arc melted	23
14.73V	--	0.1687	Du Pont, hot rolled	23
15.3V	--	0.1734	--	10
21.0V	--	0.1728	Du Pont, arc melted	23
21.0V	--	0.1716	Du Pont, hot rolled	23
21.5V	--	0.173	--	10
25.2V	--	0.176	--	10
26.1V	--	0.1754	Du Pont, arc melted	23
26.1V	--	0.1750	Du Pont, hot rolled	23
31.27V	--	0.1781	Du Pont, arc melted	23
31.27V	--	0.1782	Du Pont, hot rolled	23
31.3V	--	0.179	--	10
51.4V	--	0.189	National Lead material	23

Less data were found for the melting temperatures of alloys. Table 3 gives the melting temperatures reported for titanium and titanium alloys.

Transformation Temperature

Table 4 shows transformation temperatures for pure titanium, three commercial alloys, and a number of other alloys. The most accurate transformation temperature for pure titanium probably is 1621 F.

ELECTRICAL PROPERTIES

Resistivity

Table 5 gives the electrical-resistivity values for titanium and titanium alloys at room temperature. Additional electrical-resistivity values at room temperature are given in Table 6, along with electrical-resistivity values found for temperatures other than room temperature. The electrical-resistivity values for commercially pure titanium at room temperature ranged from about 49 to 60 microhm-cm with one exception, which was for material in wire form. The electrical resistivity of commercially pure titanium increases with temperature to the transformation temperature and then decreases. The electrical resistivity of titanium alloys covers a wide range of values.

Thermoelectric Force

Table 7 shows the thermoelectric force of titanium versus platinum for a number of temperatures, as given by Adenstedt[15].

MAGNETIC PROPERTIES

Permeability

Table 8 gives magnetic-permeability values for titanium and three commercial alloys.

Susceptibility

Table 9 shows magnetic susceptibility for titanium, titanium with 2 weight per cent silicon, and with 2.5 weight per cent hydrogen added to the silicon alloy.

TABLE 3. MELTING TEMPERATURES OF TITANIUM AND TITANIUM ALLOYS

Composition (Balance Ti), weight per cent	Alloy Designation	Melting Temperature, F	Reference
Pure Ti	--	3165(a)	1, 2, 12, 24 through 34
Commercially pure Ti	--	3097(b)	12, 15, 21, 35, 36
Commercially pure Ti	Ti-75A	3020 ± 18	37
2Al	--	3110	38
3Al-5Cr	MST-3Al-5Cr	3000-3045	13
4Al-4Mn	C-130AM	2820-3000	13
4Al-4Mn	C-130AM	2910-3090	9, 12
5Al	--	3074	38
5Al	--	3110	29
10Al	--	3020	38
10Al	--	3092	29
15Al	--	2966	38
20Al	--	2930	38
20Al	--	3074	29
30Al	--	2750	38
30Al	--	2912	29
36Al	--	2600	16
40Al	--	2624	38
40Al	--	2696	29
50Al	--	2588	38
2.1Cr-2.2Fe-2.0Mo	Ti-140A	3002	13
2.8Cr-1.5Fe	Ti-150A	2950	39
2Fe-3.8Mn	--	3072	40
4Fe-13.2Mn	--	2595	40
4Fe-28.5Mn	--	2444	40
8Fe-9.6Mn	--	2661	40
8Fe-21.7Mn	--	2160	40
12Fe-13.8Mn	--	2079	40
14Fe-11.8Mn	--	2530	40
14Fe-13.1Mn	--	2352	40
14Fe-18.9Mn	--	2277	40
18Fe-15.7Mn	--	2138	40
20Fe-4.9Mn	--	2066	40
20Fe-8.2Mn	--	2194	40
20Fe-13.2Mn	--	1918	40
20Fe-17.8Mn	--	2032	40
20Fe-23.0Mn	--	2253	40
20Fe-31.5Mn	--	2286	40
30Fe-2.0Mn	--	1900	40
30Fe-6.0Mn	--	2044	40
30Fe-13.4Mn	--	2350	40
30Fe-20Mn	--	2007	40
30Fe-25.6Mn	--	2183	40
8Mn	C-110M	2730-2970	20
8Mn	C-110M	2730-2910	13
8Mn	C-110M	2550-2740	12
10Mo-1 O_2	--	3290	40
10Mo-4 O_2	--	3360	40
10Mo-7 O_2	--	3261	40
10Mo-10 O_2	--	3281	40
19Mo-1 O_2	--	3301	40
19Mo-4 O_2	--	>3990	40
19Mo-7 O_2	--	3211	40
19Mo-10 O_2	--	3340	40
31Mo-1 O_2	--	2581-2750	40
31Mo-4 O_2	--	3191	40
31Mo-7 O_2	--	>3990	40
3.14V	--	2966	22
14.8V	--	2921	22
20.0V	--	2894	22
21.0V	--	2876	22
26.1V	--	2863	22
31.0V	--	2870	22

(a) Average of 17 values, ranging from 3020 to 3317 F.
(b) Average of 5 values ranging from 3040 to 3135 F.

TABLE 4. TRANSFORMATION TEMPERATURES OF TITANIUM AND TITANIUM ALLOYS

Composition (Balance Ti), weight per cent	Alloy Designation	Transformation Temperature, F	Reference
Pure Ti	--	1615	41
Pure Ti	--	1621[a]	6
Pure Ti	--	1630	29
2 Al-2Mn	--	1697±45[b]	42
2Al-4Mn	--	1652±45[b]	42
2Al-6Mn	--	1562±45[b]	42
2Al-0.3Si	--	1652±45[c]	43
2Al-0.6Si	--	1652±45[c]	43
2Al-0.9Si	--	1652±45[c]	43
2Al-0.3Si	--	1742±45[b]	42
2Al-0.6Si	--	1742±45[b]	42
2Al-0.9Si	--	1742±45[b]	42
3Al-5Cr	--	1598±45[b]	42
4Al-2Mn	--	1787±45[b]	42
4Al-4Mn	C-130AM	1750-1800	13
4Al-4Mn	--	1697±45[b]	42
4Al-6Mn	--	1652±45[b]	42
4Al-0.3Si	--	1742±45[c]	43
4Al-0.6Si	--	1742±45[c]	43
4Al-0.9Si	--	1742±45[c]	43
4Al-0.3Si	--	1832±45[b]	42
4Al-0.6Si	--	1832±45[b]	42
4Al-0.9Si	--	1832±45[b]	42
5Al	--	1767	29
6Al-0.3Si	--	1787±45[c]	43
6Al-0.6Si	--	1787±45[c]	43
6Al-0.9Si	--	1787±45[c]	43
6Al-0.3Si	--	1922±45[b]	42
6Al-0.6Si	--	1922±45[b]	42
6Al-0.9Si	--	1922±45[b]	42
8Al	--	1924	29
2.8Cr-1.5Fe	Ti-150A	1400-1700	13
8Mn	C-110M	1500[d]	13

(a) Average of eight measurements, probably best value.
(b) $\beta/\alpha + \beta$
(c) $\alpha/\alpha + \beta$
(d) All in β phase

TABLE 5. ELECTRICAL RESISTIVITY OF TITANIUM AND TITANIUM ALLOYS AT ROOM TEMPERATURE

Composition (Balance Ti), weight per cent	Alloy Designation	Resistivity, microhm-cm	Remarks	Reference
Commercially pure Ti	Ti-75A	60	—	44
Commercially pure Ti	Ti-100A	58	—	44
Commercially pure Ti	Ti-175A	60	—	44
1.186Ag	—	55.3	—	44
2.422Ag	—	60.6	—	44
3.381Ag	—	64.1	—	44
4.266Ag	—	63.9	—	44
5.545Ag	—	71.0	—	44
6.450Ag	—	75.9	—	37
7.573Ag	—	73.4	—	37
8.457Ag	—	79.1	—	9
0.186Al	—	78.0	—	45
0.260Al	—	56.2	—	44
0.486Al	—	61.8	—	44
0.833Al	—	69.4	—	44
0.964Al	—	72.2	—	44
1.073Al	—	81.3	—	44
1.245Al	—	80.8	—	44
1.515Al	—	90.7	—	44
1.798Al	—	89.6	—	44
1.990Al	—	92.0	—	44
2.0Al-2Fe	MST-2Al-2Fe	118.0	—	9
2.0Al-2Fe	MST-2Al-2Fe	120.0	—	12
2.0Al-2Fe	MST-2Al-2Fe	120-125	—	8
2.0Al-4V	—	108	As received	46
2.514Al	—	96.3	—	44
2.64Al	—	128.0	—	45
3.0Al-5Cr	MST-3Al-5Cr	145-150	—	8
3.0Al-5Cr	MST-3Al-5Cr	145-150	—	13
3.0Al-5Cr	MST-3Al-5Cr	140	—	12
3.0Al-5Cr	MST-3Al-5Cr	140	—	9
4.0Al-4Mn	C-130AM	154	—	13
0.1B	—	58	—	45
0.5B	—	58	—	45
0.37Be	—	66	—	45
0.5Be	—	66	—	45
1.07Be	—	65	—	45
1.28C	—	61	—	45
0.402Ca	—	57.6	—	44
0.914Ca	—	63.6	—	44
0.947Ca	—	67.1	—	44
1.519Ca	—	77.0	—	44
1.536Ca	—	81.6	—	44
2.160Ca	—	95.5	—	44
2.261Ca	—	94.3	—	44
2.354Ca	—	95.1	—	44
2.641Ca	—	92.9	—	44
2.937Ca	—	96.7	—	44
3.132Ca	—	96.5	—	44
38Co	—	110	Pressed	18
38Co	—	51.4	Heat treated	18
2.1Cr-2.2Fe-2.0Mo	Ti-140A	79	—	37
2.1Cr-2.2Fe-2.0Mo	Ti-140A	79	—	12
2.1Cr-2.2Fe-2.0Mo	Ti-140A	79	—	8
2.8Cr-1.5Fe	Ti-150A	60	—	47
2.8Cr-1.5Fe	Ti-150A	60	—	12
2.8Cr-1.5Fe	Ti-150A	60	—	9
2.8Cr-1.5Fe	Ti-150A	60	—	8
2.8Cr-1.5Fe	Ti-150A	60	—	13
2.5Fe-2.5V	MST-2.5Fe-2.5V	80	—	12
2.5Fe-2.5V	MST-2.5Fe-2.5V	78	—	9

TABLE 5. (Continued)

Composition (Balance Ti), weight per cent	Alloy Designation	Resistivity, microhm-cm	Remarks	Reference
2.5Fe-2.5V	MST-2.5Fe-2.5V	80-85	—	8
0.98In	—	92	—	45
3.53Mn	—	88	—	45
4.30Mn	—	93	—	45
4.74Mn	—	102	—	48
5.62Mn	—	116	—	45
6.02Mn	—	105	—	45
7.22Mn	—	118	—	45
8Mn	—	94	As received	46
8Mn	—	95	As received	46
8Mn	C-110M	92.5	—	13
10.21Mo	—	80	—	45
12.52Mo	—	98	—	45
38.0Ni	—	165	Pressed	18
38.0Ni	—	160	Heat treated	18
0.5Si	—	63	—	45
1.06Si	—	95	—	45
0.5V	—	73	—	45
1.20V	—	72.5	86.9% H.R.	22
1.20V	—	68.6	800 C anneal	22
2.5V	—	87.8	85.5% H.R.	22
2.5V	—	86.1	800 C anneal	22
4.2V	—	107.3	90.6% H.R.	22
4.2V	—	81.0	800 C anneal	22
5.0V	—	87.0	—	45
7.6V	—	87.8	800 C anneal	22
7.6V	—	121.2	85.1% H.R.	22
7.6V	—	102.0	800 C anneal	22
14.8V	—	182.6	77.4% H.R.	22
14.8V	—	111.1	800 C anneal	22
20.0V	—	196.6	92.2% H.R.	22
21.0V	—	172.4	77.8% H.R.	22
21.0V	—	173.4	77.8% H.R.	22
21.0V	—	171.2	800 C anneal	22
21.0V	—	175.5	77.8% H.R.	22
26.1V	—	158.6	87.3% H.R.	22
26.1V	—	157.4	87.3% H.R.	22
31.0V	—	153.8	89.0% H.R.	22
10.0Zr	—	76.0	—	45
20.0Zr	—	80.0	—	45
30.0Zr	—	94.0	—	45
40.0Zr	—	115.0	—	45

TABLE 6. ELECTRICAL RESISTIVITY OF TITANIUM AND TITANIUM ALLOYS AT VARIOUS TEMPERATURES

Composition (Balance Ti), weight per cent	Alloy Designation	Electrical Resistivity, microhm-cm, at Indicated Temperature																Remarks	References
		–400 F	–300 F	–200 F	–100 F	32 F	68 F	200 F	400 F	600 F	800 F	1000 F	1200 F	1400 F	1600 F	1800 F	2000 F		
Commercially pure Ti	Iodide	–	12.3	23.0	35.6	52.3	56.7	73.4	98.6	123.6	145.0	161.8	175.2	185.0	189.2	172.9	173.7	–	49
Commercially pure Ti	–	–	15.2	25.3	35.5	48.8	52.2	65.7	85.9	105.8	125.4	140.3	152.2	161.0	169.5	152.6	154.5	–	49
Commercially pure Ti	A-70 (RC-70)	–	–	–	–	–	55.5	67.7	87.6	106.8	123.8	138.2	150.4	159.2	159.2	150.0	151.1	–	15
Commercially pure Ti	A-70 (RC-70)	–	–	–	–	–	55.0	67.0	87.0	106.0	124.0	138.0	150.0	159.0	159.0	150.0	151.0	–	50
Commercially pure Ti	RC-55	–	–	–	–	–	48.6	62.6	82.5	101.0	117.7	132.6	145.3	–	–	–	–	–	15
Commercially pure Ti	Ductile	–	18.1	27.0	36.8	50.0	53.3	67.9	–	–	–	–	–	–	–	–	–	Material A	51
Commercially pure Ti	Ductile	–	18.7	28.7	38.5	51.8	55.2	68.5	88.5	106.9	124.2	140.0	152.3	162.0	–	–	–	Material B	51
Commercially pure Ti	Wire	–	–	–	–	–	78.5	92.2	111.2	128.9	144.5	157.2	168.1	177.8	181.8	178.2	175.0	–	52
Commercially pure Ti	Annealed	–	–	–	–	–	49.0	62.3	82.4	102.8	121.9	137.5	150.8	161.3	–	–	–	Annealed 12 hr 1200-1300 F, data on heating	53
Commercially pure Ti	Annealed	–	–	–	–	–	49.9	63.1	82.9	102.3	121.8	138.0	151.1	161.4	–	–	–	Annealed 12 hr 1200-1300 F, data on cooling	53
Commercially pure Ti	Annealed	–	–	–	–	–	51.1	64.3	84.5	104.5	123.8	139.8	152.7	162.8	–	–	–	Annealed 10 hr 1247-1292 F, data on heating	53
Commercially pure Ti	Annealed	–	–	–	–	–	57.5	71.0	91.0	111.3	128.2	142.8	154.2	162.8	–	–	–	Annealed 8 hr 1300-1337 F, data on heating	53
2Al-4V	–	–	–	85	100	–	115	–	–	–	–	–	–	–	–	–	–	Heat treated	46
2Al-4V	–	–	–	88	98	–	114	–	–	–	–	–	–	–	–	–	–	Heat treated	46
2Al-4V	–	–	–	84	98	–	115	–	–	–	–	–	–	–	–	–	–	Heat treated	46
4Al-4Mn	C-130AM (RC-130B)	144	149	154	159	–	167	–	–	–	–	–	–	–	–	–	–	–	54
4Al-4Mn	C-130AM (RC-130B)	–	–	–	–	–	157.8	160.7	167.3	173.1	176.3	177.3	177.5	175.6	170.1	166.5	170.0	–	15
4Al-4Mn	C-130AM (RC-130B)	–	–	–	–	–	146.1	151.4	158.4	162.2	168.1	170.0	159.3	157.8	152.6	148.3	151.0	–	55
5Al-2.5Sn	A-110AT	–	–	–	–	–	157.3	162.5	170.7	177.5	182.8	186.0	187.9	188.5	188.4	181.4	173.0	–	56
8Mn	C-110M (RC-130A)	–	–	–	–	–	90.7	101.6	117.3	131.0	141.3	149.0	154.7	156.2	153.9	155.3	157.0	–	20
8Mn	–	–	–	166.0	178.0	–	174.0	–	–	–	–	–	–	–	–	–	–	Heat treated	46
8Mn	–	–	–	–	177.0	–	175.0	–	–	–	–	–	–	–	–	–	–	–	46

TABLE 7. THERMOELECTRIC FORCE OF TITANIUM VERSUS PLATINUM[15]

Temperature, F	Thermoelectric Force, millivolts	Temperature, F	Thermoelectric Force, millivolts
-300	-0.5	600	3.9
-200	-0.6	800	5.2
-100	-0.4	1000	6.4
32[a]	0	1200	7.6
68	0.2	1400	9.0
200	1.0	1600	10.6
400	2.5	1800	12.5

(a) Reference temperature.

TABLE 8. MAGNETIC PERMEABILITY OF TITANIUM AND TITANIUM ALLOYS

Composition (Balance Ti), weight per cent	Alloy Designation	Permeability	Reference
Ti	--	1.0001	2
Commercially pure Ti	A-70	1.00005[a]	57
Commercially pure Ti	Ti-75A	1.0001	37
4Al-4Mn	C-130AM	1.00005[a]	57
5Al-2.5Sn	A-110AT	1.00005[a]	57
8Mn	C-110M	1.00005[a]	57

(a) At 20 oersteds, hot rolled and annealed.

TABLE 9. MAGNETIC SUSCEPTIBILITY OF TITANIUM AND TITANIUM ALLOYS

Composition (Balance Ti), weight per cent	Magnetic Susceptibility $x10^6$, cgs units, at Indicated Temperature										Reference
	-300 F	-100 F	32 F	68 F	81 F	400 F	800 F	1200 F	1600 F	2000 F	
Ti	1.70	1.25	1.25	1.25	—	—	—	—	—	—	58
2Si	3.1	3.2	—	3.3	—	3.4	3.7	4.0	4.5	5.2	59
2Si	—	—	—	—	3.2	—	—	—	—	—	60
2Si-2.5H	—	—	—	—	3.78	—	—	—	—	—	60

OPTICAL PROPERTIES

Emissivity

Table 10 shows spectral and total emissivity values for titanium. No emissivity values for titanium alloys were found.

SOUND

Velocity

Fusfeld and Gilbert(63) give the following values for the velocity of sound in titanium:

Specimen Number	Velocity of Sound, ft per sec
1	16, 350
2	16, 349
3	16, 273
4	16, 299

An analysis of the specimens showed them to contain the following:

0.01 to 0.1 weight per cent Fe, Si, and Cu

0.001 to 0.01 weight per cent Mn

Less than 0.1 weight per cent Mg, Al, and Ni.

THERMAL PROPERTIES

Conductivity

Table 11 shows thermal-conductivity values for titanium and titanium alloys. In general, the addition of alloying elements reduces the thermal conductivity of titanium.

Diffusivity

McIntosh, et al.,[66] gives the diffusivity of titanium as follows:

Temperature, F	Diffusivity, ft^2/hr
1057	0.24
1300	0.23
1542	0.19, 0.21

Expansion

Table 12 shows mean-linear-expansion coefficients from 68 F to the indicated temperatures for titanium and titanium alloys.

Heat of Fusion

Ogden and Gonser[1] give the heat of fusion for titanium as 5000 cal/mole.

Specific Heat

Table 13 shows specific-heat values for titanium and titanium alloys.

Heat of Vaporization

Table 14 shows values for the heat of vaporization of titanium and the corresponding pressures.

TABLE 10. EMISSIVITY OF TITANIUM

Material	Spectral Emissivity, $\lambda = 0.65\ \mu$	Temperature, F	Remarks	Reference
Ti	0.43	2400-2716	Average of eight measurements, range of values 0.41 to 0.45	61
Ti	0.484	1742		62
Ti	0.482	1832		62
Ti	0.479	2012		62
Ti	0.476	2192		62
Ti	0.473	2372		62
Ti	0.471	2462		62
Ti	0.475 ± 0.010	1652-2732		34
Ti, pure iodide	0.440	2380		6
Ti, pure iodide	0.414	2714		6
Ti, commercially pure	0.63	1430-2060		6
Ti, commercially pure	0.49	2060		6
Ti, commercially pure	0.549	1580	α phase	6
Ti, commercially pure	0.484	1742		6
Ti, commercially pure	0.471	2642	β phase	6
	Total Emissivity			
Ti	0.31	81		6
Ti	0.33	1431		6
Ti	0.40	1881		6

TABLE 11. THERMAL CONDUCTIVITY OF TITANIUM AND TITANIUM ALLOYS

Composition (Balance Ti), weight per cent	Alloy Designation	Thermal Conductivity, Btu per hr per ft^2 per ft per F, at Indicated Temperature													Reference
		-400 F	-300 F	-200 F	-100 F	32 F	68 F	200 F	400 F	600 F	800 F	1000 F	1200 F	1400 F		
Commercially pure Ti			11.0		12.0		11.3	9.3	8.7	8.6	8.7	8.8				6
Commercially pure Ti								8-10								9, 12, 64
Commercially pure Ti								10.3								15
Commercially pure Ti								8.85								25
Commercially pure Ti	A-70				10.3		9.9	9.8	9.7	9.8	10.0	10.5	11.2	11.9	12.4[a]	50
Commercially pure Ti	RC-55							11.0	11.5							65
Commercially pure Ti	Ti-75A						9.84									37
Commercially pure Ti	Ti-175A						8-10									9
4Al-4Mn	C-130AM			3.5[b]			4.0	4.5	5.25	6.25	7.25	8.25	9.25	10.5	11.25[c]	55
4Al-4Mn	RC-130B	1.64	2.76	3.48	4.09	4.77										54
5Al-2.5Sn	A-110AT				3.89	4.31		4.85	5.55	6.30	7.11	8.01	8.96	9.97	10.48[a]	56
2.8Cr-1.5Fe	Ti-150A						8-10									8, 9, 12, 13, 47
2.8Cr-1.5Fe	Ti-150A						8.9									39
2.8Cr-1.5Fe	Ti-150A								9.5	9.6	9.9	9.8	9.9			65
8Mn	C-110M						6.3	6.7	7.4	8.1	8.8	9.8	10.3	11.3		20

(a) At 1500 F.
(b) At 180 F.
(c) At 1550 F.

TABLE 12. MEAN LINEAR THERMAL EXPANSION COEFFICIENTS

Composition, (Balance Ti), weight per cent	Alloy Designation	Mean Linear Thermal Expansion Coefficient				
		-400 F	-300 F	-200 F	-100 F	200 F
Iodide, Ti						
Ti						
Ti						
Ti						5.1
As deposited, cold swaged, unannealed Ti		3.2	3.8	4.2	4.5	
Commercially pure Ti						
Commercially pure Ti	A-70					4.75
Unalloyed Ti	RC-55				4.4	4.7
Unalloyed Ti	RC-70				3.9	4.8
2Al-2Fe	MST-2Al-2Fe					6.4(b)
2Al-2Fe	MST-2Al-2Fe					5.4(b)
3Al-5Cr	MST-3Al-5Cr					5.0(b)
3Al-5Cr	MST-3Al-5Cr					6.0(b)
4Al-4Mn	C-130AM					4.9
4Al-4Mn	C-130AM					4.8
4Al-4Mn	C-130AM		5.6	6.4	7.0	
5Al-2.5Sn	A-110AT					5.2
6Al-4V	MST-6Al-4V					
6Al-4V						
6Al-4V						4.6
6Al-4V						4.6
6Al-4V						4.2
6Al-4V						4.6
0.04C						5.1
10Cb						4.67
1Cr-1Fe-1Mn-1Mo-1V	3Mn complex					4.5
2.1Cr-2Mo-2.2Fe	Ti-140A					4.9 to 5.1(b)
2.6Cr-1.3Fe						
2.8Cr-1.5Fe	Ti-150A		4.4	5.0	5.4	
3Cr-1.5Fe	Ti-150B					5.0(b)
5Cr						
10Cr						
15Cr						
40Cr						
5Cu						
2.5Fe-2.5V	MST-2.5Fe-2.5V					5.1(b)
2.5Fe-2.5V	MST-2.5Fe-2.5V					5.3(b)
2.5Mn						
7Mn	RS-120					
8Mn	C-110M					4.8
8Mn	C-110M					
5Mo						
2.5Ni						
7.5Ni						
10Ni						
1Si						
3Si						
10Zr						

Footnotes appear on the following page.

OF TITANIUM AND TITANIUM ALLOYS

x 10^6/F Between 68 F and Indicated Temperature											
400 F	600 F	800 F	1000 F	1200 F	1400 F	1600 F	1800 F			Notes	Reference
4.80	4.95	5.16	5.29	5.41	5.53	5.67					15
8.1											41
4.21	4.39	4.61	4.80	5.02	5.22	5.41					67
5.2	5.3	5.5	5.6	5.8							68
											23
4.87	4.94	5.11	5.29	5.41	5.69	5.60					15
5.20	5.45	5.60	5.75	5.9	6.10	6.40	6.50				50
5.2	5.3	5.4	5.5	5.6	5.7	5.8	(5.8)[a]				15
5.2	5.2	5.2	5.4	5.5	5.6	5.7	(6.0)[a]				15
											12
											8,9
											8,9,13
											12
4.9	5.1	5.3	5.4	5.6	5.8	(5.7)[a]	(5.3)[a]				15,55
											13
											70
5.2	5.3	5.3	5.4	5.5	5.6	5.7	(5.7)[a]				56
								5.2[c]	5.8[d]		13
			4.7								46
4.8	5.0	5.1	5.0	5.0	5.1			5.1[e]		(f)	69
5.0	5.0	5.1	5.2	5.3	5.6			5.6[e]		(g)	69
4.1	4.3	4.7	5.2	5.4	5.3			5.7[e]		(h)	69
4.9	4.9	5.0	5.1	5.3	5.4			5.4[e]		(i)	69
5.2	5.3	5.5	5.6	5.8						(j)	68
4.78	5.01	5.26	5.29	5.28	5.25[a]					(j)	15
4.7	4.8	5.0	5.1	6.6	9.0						
								5.0[k]		(j)	8
4.93	4.98	5.06	5.14	5.33	(4.97)[a]					(j)	15
										(j)	70
										(j)	9
4.83	5.08	5.34	5.52	(5.48)[a]	(5.62)[a]	(5.58)[a]				(j)	15
5.07	5.27	5.56	5.74	(6.40)[a]	(5.73)[a]					(j)	15
5.15	(5.09)[a]	(5.90)[a]	(6.22)[a]	(6.87)[a]	(6.38)[a]	(6.40)[a]				(j)	15
4.64	4.79	5.38	5.47	(6.24)[a]	(5.85)[a]	(5.83)[a]				(j)	15
5.06	5.13	5.26	5.45	5.58	5.78	(5.82)[a]				(j)	15
											8,9
											12
4.95	5.12	5.32	5.50	5.67	5.76	(5.54)[a]				(j)	15
								4.65[k]			13
5.1	5.4	5.7	6.0	6.5	(6.9)[a]	(7.1)[a]	(7.4)[a]				20
5.5	6.2	6.7	7.8	8.7	9.2	9.4					14
4.77	4.93	5.09	5.25	5.34	5.40	(5.37)[a]				(j)	15
4.60	4.82	5.04	5.23	5.45	(5.48)[a]	(5.65)[a]				(j)	15
4.82	5.01	5.21	5.45	(5.79)[a]	(5.85)[a]	(5.39)[a]				(j)	15
4.92	5.08	5.23	5.38	(5.49)[a]	(5.43)[a]	(5.08)[a]				(j)	15
4.99	5.04	5.27	5.40	5.51	5.64	5.72				(j)	15
4.81	4.97	5.16	5.34	5.50	5.69	5.74				(j)	15
4.71	4.88	5.07	5.24	5.40	5.56	5.65				(j)	15

Footnotes for Table 12

(a) Into transformation range.
(b) Temperature not given — assumed to be room temperature.
(c) 90-932 F.
(d) 932-1652 F.
(e) At 1500 F.
(f) As received.
(g) Heat treated.
(h) Cold worked.
(i) Second run on as-received material.
(j) Completely stabilized.
(k) 200-600 F.

TABLE 13. SPECIFIC HEAT OF

Composition (Balance Ti), weight per cent	Alloy Designation	Specific Heat,					
		-400 F	-300 F	-200 F	-100 F	32 F	68 F
99 Ti	-	0.0069	0.0655	0.0945	0.1105		
99 Ti	-						
99 Ti	-						
Commercially pure Ti	RC-55					0.127	
Commercially pure Ti	A-70 (RC-70)					0.122	0.123
Commercially pure Ti	Ti-75A						0.129
Commercially pure Ti	Ti-175A						0.129
4Al-4Mn	C-130AM						0.128
4Al-4Mn	RC-130B					0.128	
5Al-2.5Sn	A-110AT					0.126	
5Al-2.5Sn	A-110AT					0.126	
2.8Cr-1.5Fe	Ti-150A						0.129
3.0Cr-1.5Fe	Ti-150B						0.129
8Mn	C-110M (RC-130A)						
8Mn	C-110M (RC-130A)					0.112	
8Mn	C-110M (RC-130A)						0.118

(a) Mean value between 32 F and indicated temperature.

TITANIUM AND TITANIUM ALLOYS

Btu/lb/F, at Indicated Temperature									
200 F	400 F	600 F	800 F	1000 F	1200 F	1400 F	1550 F	1800 F	Reference
									71
				0.141[a]					31
		0.1334[a]							35
0.130	0.136	0.143	0.151	0.160	0.171	0.183	0.193		15
0.130	0.138	0.144	0.149	0.154					50
									37
									9
0.133	0.139	0.148	0.157	0.168	0.181	0.195	0.207		55
0.133	0.139	0.148	0.157	0.168	0.181	0.195	0.207		36
0.131	0.137	0.145	0.153	0.161	0.170	0.180	0.188		56
			0.153		0.170		0.188		13
									8, 9, 12, 13
									9
0.112[a]									36
0.130	0.141	0.147	0.153	0.166	0.192	0.236	0.286		36
									20

TABLE 14. HEAT OF VAPORIZATION OF TITANIUM

Temperature, F	Pressure, atmospheres x 10^8	H, cal per mole	Reference
2398	0.773	112,874	6
2464	1.864	112,592	6
2503	3.23	112,613	6
2542	4.25	112,761	6
2556	5.05	112,728	6
2597	7.91	112,706	6
2646	13.24	112,684	6
2716	26.3	112,762	6
	Average	112,715	

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<u>LIST OF TML REPORTS</u>

The list below describes all reports that have been prepared thus far by the Titanium Metallurgical Laboratory. The reports indicated by a star may be obtained by addressing a request to:

Titanium Metallurgical Laboratory
Battelle Memorial Institute
505 King Avenue
Columbus 1, Ohio

	Report Number	Title
	1A	Visits of Steering Group to Aircraft Manufacturers (TML No. 1 revised)
	2	First Progress Statement to Steering Group, February, 1955
	3	Second Progress Statement to Steering Group, March, 1955
	4	Notes on the Fabrication and Use of Titanium (To the Materials Advisory Board of the National Academy of Science)
Out of Print ★	5A	The Use of Titanium Alloy Sheet in Airframe Components (TML No. 5 revised) (Superseded by TML Nos. 13 and 24)
	6	Third Progress Statement to Steering Group, April, 1955
★	7	Survey of the Problem of Delayed Cracking in Formed Titanium Parts
★	8	Principles and Practical Aspects of Titanium Heat Treatment
	9	Fourth Progress Statement to Steering Group, May, 1955
★	10	A Study of the Air Contamination of Three Titanium Alloys
	11	Report to the Steering Group on Titanium Fasteners
★	12	Formability Tests on Titanium Alloy Sheet
★	13	Selection of Materials for High-Temperature Applications in Airframes
★		Supplement to TML Report No. 13
	14	Fifth Progress Statement to Steering Group, June, 1955
★	15	Engineering Properties of Commercial Titanium Alloys
	16	Recommendation for Augmented Research and Development on Titanium
	17	Sixth Progress Statement to Steering Group, July, 1955
★	18	Analysis and Laboratory Examination of Aircraft Parts Which Failed by Delayed Cracking
★	19	General Summary of the Physical Metallurgy of Titanium Alloys
★	20	Effect of Carbon, Oxygen, and Nitrogen on the Mechanical Properties of Titanium and Titanium Alloys
★	21	The Diffusion of Interstitial and Substitutional Elements in Titanium
★	22	Selective Standardization and Status of Specifications for Titanium Mill Products
	23	Seventh Progress Statement to Steering Group, August, 1955
★	24	The Application of a New Structural Index to Compare Titanium Alloys With Other Materials in Airframe Structures
★	25	Beta Transformation in Titanium Alloys
	26	Eighth Progress Statement to Steering Group, September, 1955
★	27	Effect of Hydrogen on the Properties of Titanium and Titanium Alloys
	28	Ninth Progress Statement to Steering Group, October, 1955
★	29	The Oxidation of Titanium and Titanium Alloys
★	30	Flow Properties, Deformation Textures, and Slip Systems of Titanium and Titanium Alloys
★	31	Welding of Titanium and Its Alloys
	32	Tenth Progress Statement to Steering Group, November, 1955
	33	Eleventh Progress Statement to Steering Group, December, 1955
★	34	Antigalling Coatings and Lubricants for Titanium, March, 1956
★	35	A Discussion of the Design of Riveted and Bolted Joints in Titanium Sheet, February, 1956
	36	First Annual Report 1955-1956, February, 1956
	37	Twelfth Progress Statement to Steering Group, January, 1956
★	38	Material Properties for Design of Airframe Structures to Operate at High Temperatures, March, 1956
★	39	Survey of Physical-Property Data for Titanium and Titanium Alloys, March, 1956

PHYSICAL-PROPERTY DATA FOR TITANIUM AND TITANIUM ALLOYS
(A Supplement to TML Report No. 39, "Summary of Physical-Property Data for Titanium and Titanium Alloys", March, 1956)

A recent review of the physical properties section in the Titanium Metallurgical Laboratory Information Center files showed that some additional information has become available since the appearance of TML Report No. 39, "Summary of Physical-Property Data for Titanium and Titanium Alloys", March, 1956. This information, supplementary to TML 39, follows.

Thermal Expansion

New data by Stanton[(1)]* on the thermal expansion of six alloys are presented in Table 1. The alloys are MST-3Al-5Cr (Ti-3Al-5Cr), 3Mn Complex (Ti-3Mn-1Fe-1Cr-1V-1Mo), Ti-140A (Ti-2.1Cr-2.2Fe-2.0Mo), A-110AT (Ti-5Al-2.5Sn), C-130AM (Ti-4Al-4Mn), and Ti-155A (Ti-5Al-1.5Fe-1Cr-1Mo). The data in the table show that the expansion coefficient of the 3Mn complex alloy, which is not a commercial alloy, doubled in magnitude in the temperature range shown. In contrast, there was little change in the other alloys for the temperature range investigated. The composition of the particular materials tested in collecting the data of Table 1 are shown in Table 2.

Specific Heat

Data for the specific heat at elevated temperature of Rem-Cru's commercially pure titanium with yield strengths of 55,000 psi and 70,000 psi were presented in TML Report No. 39. The only other published data on the specific heat of unalloyed titanium are the early measurements of Jaeger, Rosenbohm, and Fonteyne.[(2)] It is quite probable that the titanium used by Jaeger, et al., in their study was not pure. Therefore, their data are not included in this compilation.

The need for data on the specific heat of titanium at elevated temperature was partially satisfied by information from B. A. Staskiewicz' Carnegie Tech doctoral dissertation[(3)] recently received by TML. The new data were obtained on high-purity titanium but show an anomaly in that a maximum occurred in the specific heat-temperature curve at about 525 C (975 F). This behavior is unusual in metals and would indicate that the new data should be used with some caution until they have been verified by other investigators. (This maximum should not be confused with the break that occurs at the alpha-beta transformation in a continuous curve of specific heat versus temperature.) The data on the specific heat of alpha titanium at elevated temperature are presented in Table 3. The heat capacity of beta titanium is constant at 8.00 cal/mole/deg K for the temperature range of 882 to 1027 C (1620 to 1870 F).

TML Report No. 39 gives room-temperature values for the specific heat of Ti-75A (unalloyed titanium) and Ti-150A (Ti-2.8Cr-1.5Fe). E. G. Loewen[(4)] determined the following equations for the specific heat up to

*References are listed at the end of the memorandum.

760 C (1400 F). The uncertainty is $\pm(3 + 0.005\theta)$ per cent where θ is the temperature in degrees F.

$$\text{Ti-75A} : Cp = 0.125 + 4.8 \times 10^{-8} (\theta-70)^2 \text{ Btu/lb F}$$

$$\text{Ti-150 F} : Cp = 0.120 \times 4.8 \times 10^{-8} (\theta-70)^2 \text{ Btu/lb F.}$$

Thermal Conductivity

The paper by Loewen(4) also gives the thermal conductivity of five titanium alloys. The total error for the data was estimated to be 10 per cent. Figures 1 and 2 are copies of figures from a preprint of the paper. They show the thermal conductivity at various temperature levels. The compositions of the alloys used by Loewen are given in Table 4.

Melting Point

The value for the melting point of titanium presented in TML Report No. 39 requires some discussion. An average value of 1741 C (3165 F) was given. Recent, and very reliable, work indicates that titanium melts at about 1670 C (3038 F) with an uncertainty of ±10 C (18 F). The interstitial elements (O, N, and C) and some high-melting-point metals (W, Ta, Cb, etc.) raise the melting point of titanium. Most other metallic impurities lower the melting point. Consequently, melting points quoted for the earlier, less pure titanium which contained oxygen and nitrogen were as high as 1800 C (3270 F). At the present time, sponge titanium containing a low oxygen and nitrogen content, but having some metallic impurities, melts at a somewhat lower temperature than the melting temperature of about 1670 C (3038 F) for pure titanium.

Magnetic Susceptibility

Additional data have become available on the magnetic susceptibility of titanium since TML Report No. 39 was published. Values for unalloyed titanium and titanium-silver and titanium-aluminum alloys by Denny(7) are presented in Table 5.

Magneto Resistance

Table 6 gives the magneto resistance of unalloyed titanium and titanium-aluminum, titanium-silver, and titanium-gallium alloys. It should be noted that the latter are gallium (Ga) and not calcium (Ca) alloys. A misprint in Table 5, page 11, of TML Report No. 39 lists the gallium alloys as calcium alloys.

Hall Coefficient

New values for the Hall coefficient of unalloyed titanium and alloys of aluminum and silver are presented in Table 7. The Hall coefficient for high-purity titanium is $+1.82 \times 10^{-13}$ volt-cm-amp^{-1} -oersted^{-1} and is, it will be noted, positive. Previously, values of $+3.0(\pm 0.1) \times 10^{-13}$ and $+0.95 \times 10^{-13}$ volt-cm-amp^{-1}-oersted^{-1} had been reported by Scovil[(8)] and Foner,[(9)] respectively. Because the Hall coefficient is positive, it has been concluded that conduction in titanium is primarily by holes, i.e., positive carriers. This is not necessarily true, because conduction in metals is normally by electrons and the positive coefficient may be due to the anisotropic nature of the titanium crystal lattice. In support of the normal electronic conduction, measurement of the absolute thermoelectric power of Ti-4Al-4Mn (RC-130B) at low temperatures gives a negative sign and indicates that electric conduction is primarily by electrons rather than holes. Values for the thermoelectric power, reported by Tyler, of Ti-4Al-4Mn are presented in Table 8.

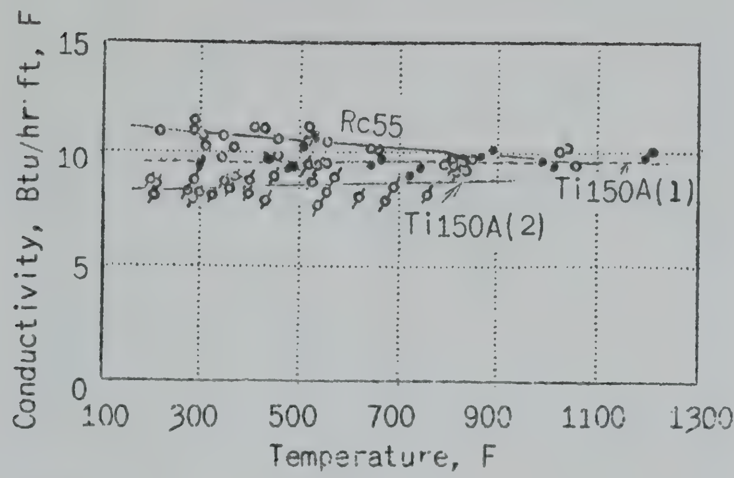

FIGURE 1. Thermal conductivity of Ti150A and RC55 titanium alloys.

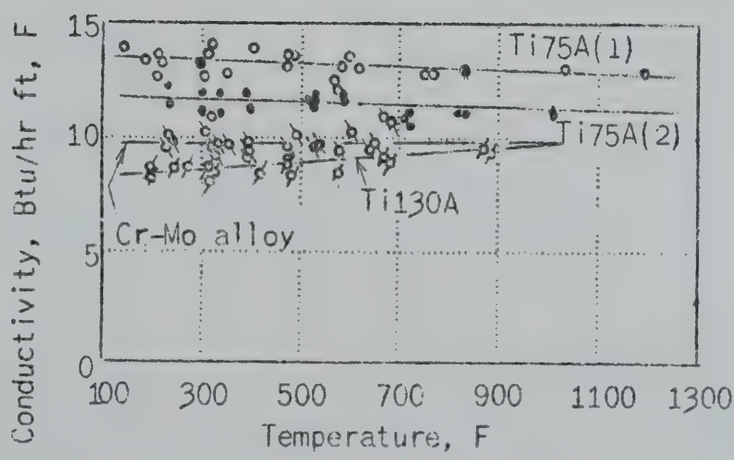

FIGURE 2. Thermal conductivity of Ti75A, Ti130A, and Cr-Mo titanium alloys.

TABLE 1. COEFFICIENTS OF THERMAL EXPANSION OF TITANIUM ALLOYS[1]

Temperature Range, F	Mean Coefficient of Linear Expansion, in/in/F, 10^{-6}					
	Ti-140A[a]	Ti-3Al-5Cr[b]	Ti-3Mn Complex[c]	A-110AT[d]	C-130AM[e]	Ti-155A[f]
77-200	4.6	5.0	4.5	5.7	4.6	4.6
77-300	4.6	5.0	4.7	5.4	5.0	5.0
77-400	4.5	5.0	4.7	5.4	4.9	4.9
77-500	4.5	5.0	4.7	5.1	4.8	4.8
77-600	4.5	5.1	4.8	5.3	4.9	4.9
77-700	4.3	5.1	4.9	5.2	5.0	5.0
77-800	4.5	5.2	5.0	5.4	5.0	5.1
77-900	4.9	5.4	5.0	5.1	4.9	5.0
77-1000	5.0	5.5	5.1	5.2	4.9	5.1
77-1100	4.9	5.8	5.4	5.3	4.8	5.0
77-1200	4.5	5.9	6.6	5.3	4.9	4.9
77-1300	4.4	5.4	7.9	5.4	4.8	4.8
77-1350	-	6.6	-	-	-	-
77-1400	4.4	-	9.0	5.6	4.7	4.7
77-1480	4.9	-	9.2	-	-	-
77-1500	-	-	-	5.6	4.9	4.7

(a) Ti-2Fe-2Cr-2Mo.
(b) Ti-3Al-5Cr.
(c) Ti-3Mn-1Fe-1Cr-1V-1Mo.
(d) Ti-5Al-2.5Sn
(e) Ti-4Al-4Mn.
(f) Ti-5Al-1.5Fe-1Cr-1Mo.

TABLE 2. CHEMICAL COMPOSITION OF ALLOYS USED IN THERMAL-EXPANSION STUDIES SUMMARIZED IN TABLE 1[1]

Alloy	Composition, per cent									
	Al	Sn	Mn	Fe	Cr	Mo	C	N	O	H (ppm)
Ti-140A	-	-	-	2.23	1.99	2.24	.05	.015	-	50
Ti-3Al-5Cr	3.47	-	-	.25	4.94	-	.05	.036	-	193
Ti-3Mn Complex	-	-	3.79	1.06	1.48	1.16	.015	.021	-	220
A-110AT	4.69	2.09	-	-	-	-	.08	.026	.11	108
Ti-155A	5.11	-	-	1.44	1.28	1.16	.037	.017	-	180
C-130AM	4.3	-	4.6	-	-	-	.10	.05	-	64

TABLE 3. HEAT CAPACITY OF ALPHA TITANIUM[3]

Temperature, K	Heat Capacity (C_p), cal./mole/degree K
300	6.153
350	6.496
400	6.711
450	6.852
500	6.947
550	7.011
600	7.055
650	7.085
700	7.104
750	7.115
800	7.121
850	7.121
900	7.119
950	7.113
1000	7.105
1050	7.095
1100	7.084
1150	7.071

TABLE 4. COMPOSITION OF TITANIUM ALLOYS USED FOR THE DETERMINATION OF THERMAL CONDUCTIVITY BY LOEWEN[4, 5, 6]

Designation of Alloy According to Loewen (Figures 1 and 2)	Composition, weight per cent								
	H	C	N	O	Fe	Cr	Mn	Mo	Ti
Ti-75A(2)[(a)]	0.0068	0.06	0.048	0.131	0.07	-	-	-	99.75
Ti-130A	0.0069	0.05	0.034	0.177	0.20	-	6.50	-	93.21
Ti-150A(2)[(a)]	0.0092	0.05	0.076	0.105	1.40	2.71	-	-	95.65
RC-55	0.0073	0.08	0.028	0.123	0.12	-	-	-	99.64
Cr-Mo	0.0077	0.02	0.032	0.131	0.13	3.38	-	2.10	96.30

(a) No analyses were made on Specimens Ti-75A(1) and Ti-150A(1).

TABLE 5. MAGNETIC SUSCEPTIBILITY OF TITANIUM AND TITANIUM ALLOYS[7]

Solute Concentration, atomic per cent	Magnetic Susceptibility, emu (cgs)
Pure Ti	3.31×10^{-6}
1.466 Al	3.27×10^{-6}
2.661 Al	3.24×10^{-6}
3.48 Al	3.22×10^{-6}
4.38 Al	3.21×10^{-6}
1.09 Ag	3.11×10^{-6}
3.51 Ag	3.14×10^{-6}
4.95 Ag	3.02×10^{-6}

TABLE 6. MAGNETO RESISTANCE OF TITANIUM AND TITANIUM ALLOYS(7)

Composition of Alloy, atomic per cent	Magneto-Resistance Coefficient, $B_t \times 10^{13}$, oersted^{-2}
Pure Ti	6.6
0.46 Al	7.0
1.47 Al	8.6
1.90 Al	8.8
2.19 Al	9.2
2.66 Al	8.8
3.15 Al	3.9
3.48 Al	2.5
4.38 Al	1.4
5.50 Al	1.5
0.48 Ga	6.8
1.09 Ga	7.2
1.13 Ga	7.0
1.81 Ga	7.2
1.83 Ga	7.5
2.57 Ga	6.9
2.80 Ga	5.6
3.14 Ga	2.6
3.49 Ga	1.4
0.53 Ag	4.0
1.09 Ag	1.9
1.53 Ag	1.6
1.94 Ag	1.1
2.54 Ag	1.7
2.97 Ag	1.4
3.51 Ag	1.5
3.94 Ag	1.4

TABLE 7. HALL COEFFICIENT OF TITANIUM AND TITANIUM ALLOYS[7]

Composition, atomic per cent	Hall Coefficient, volt-cm-amp^{-1}-oersted^{-1}
Pure Ti	1.82×10^{-13}
1.466 Al	1.90×10^{-13}
3.48 Al	1.73×10^{-13}
4.38 Al	1.51×10^{-13}
1.09 Ag	1.68×10^{-13}
3.51 Ag	1.44×10^{-13}

TABLE 8. ABSOLUTE THERMOELECTRIC POWER OF Ti-4Al-4Mn (RC-130B)[10]

Temperature, K	Absolute Thermoelectric Power, microvolts per deg. K
17.18	-0.23
19.91	-0.27
23.35	-0.51
42.37	-1.82
65.26	-2.34
78.76	-2.60
82.59	-2.68
100.6	-2.90
141.3	-3.45
196.1	-4.03
204.1	-4.05
276.3	-4.87
278.0	-4.92

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